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UNITED STATES LETTERS PATENT

FOR

SELF-CONTROLLED DIRECTIONAL DRILLING SYSTEMS AND METHODS

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BACKGROUND OF THE INVENTION

Cross Reference to Related Applications

This application is a Continuation in Part of Application Serial No. 10/334,029 filed on 12/30/2002, which is a continuation of Application Serial No. 09/438,013 filed 11/10/1999, now US Patent No. 6,513,606 B1 which claims the benefit of U.S. Provisional Application Serial No. 60/107,856, filed November 10, 1998.

Field of the Invention

This invention relates generally to drill strings for drilling directional wellbores and more particularly to a self-adjusting steerable drilling system and method for drilling directional wellbores.

Description of the Related Art

Steerable motors comprising a drilling or mud motor with a fixed bend in a housing thereof that creates a side force on the drill bit and one or more stabilizers to position and guide the drill bit in the borehole are generally considered to be the first systems to allow predicable directional drilling. However, the compound drilling path is sometimes not smooth enough to avoid problems with the completion of the well. Also,

rotating the bent assembly produces an undulated well with changing diameter, which can lead to a rough well profile and hole spiraling which subsequently might require time consuming reaming operations. Another limitation with the steerable motors is the need to stop rotation for the directional drilling section of the wellbore, which can result in poor hole cleaning and a higher equivalent circulating density at the wellbore bottom. Also, this increases the frictional forces which makes it more difficult to move the drill bit forward or downhole. It also makes the control of the tool face orientation of the motor more difficult.

The above-noted problems with the steerable drilling motor assemblies lead to the development of so called "self-controlled" or drilling systems. Such systems generally have some capability to follow a planned or predetermined drilling path and to correct for deviations from the planned path. Such self-controlled system are briefly described below. Such systems, however, enable faster, and to varying degree, a more direct and tailored response to potential deviation for directional drilling. Such systems can change the directional behavior downhole, which reduces the dog leg severity .

The so called "straight hole drilling device" ("SDD") is often used in drilling vertical holes. An SDD typically includes a straight drilling motor with a plurality of steering ribs, usually two opposite ribs each in orthogonal planes on a bearing assembly near the drill bit. Deviations from the vertical are measured by two orthogonally mounted inclination sensors. Either one or two ribs are actuated to direct the drill bit back onto the vertical course. Valves and electronics to control the actuation of the ribs

are usually mounted above the drilling motor. Mud pulse or other telemetry systems are used to transmit inclination signals to the surface. The lateral deviation of boreholes from the planned course (radial displacement) achieved with such SDD systems has been nearly two orders of magnitude smaller than with the conventional assemblies. SDD systems have been used to form narrow cluster boreholes and because less tortuous boreholes are drilled by such a system, it reduces or eliminates the reaming requirements.

In the SDD systems, the drill string is not rotated, which significantly reduces the hole breakout. The advantage of drilling vertical holes with SDD systems include: (a) a less tortuous well profile; (b) less torque and drag; (c) a higher rate of penetration; (d) less material (such as fluid) consumption; (e) less environmental impact; (f) a reduced risk of stuck pipe; (g) less casing wear, and (h) less wear and damage to drilling tubulars.

An automated drilling system developed by Baker Hughes Incorporated, the assignee of this application, includes three hydraulically-operated stabilizer ribs mounted on a non-rotating sleeve close to the drill bit. The forces applied to the individual ribs are individually controlled creating a force vector. The amount and direction of the side force are kept constant independent of a potential undesired rotation of the carrier sleeve. The force vector can be pre-programmed before running into the borehole or changed during the drilling process with commands from the surface.

This system has two basic modes of operation: (i) steer mode and (ii) hold mode. In the steer mode the steering force vector is preprogrammed or reset from the surface, thus allowing to navigate the well path. In the "hold mode" values for inclination and/or azimuth are preset or adjusted via surface-to-downhole communications, thus allowing changes to the borehole direction until the target values are achieved and then keeping the well on the target course. As the amount of side force is preset, the turn radius or the equivalent build-up rate (BUR) can be smoothly adjusted to the requirements from 0 to the maximum value of 8°/100 feet for such a system.

An automated directional drilling bottomhole assembly developed by Baker Hughes Incorporated and marketed under the brand name AUTOTRAK™ has integrated formation evaluation sensors to not only allow steering to solely directional parameters, but to also take reservoir changes into account and to guide the drill bit accordingly. The automated directional drilling bottomhole assembly may be used with or without a drilling motor. Using a motor to drive the entire assembly allows a broader selection of bits and maximizes the power to the bit. With a motor application, the string rpm becomes an independent parameter. It can be optimized for sufficient hole cleaning, the least casing wear and to minimize dynamics and vibrations of the BHA, which heavily depend on the rotational string frequency.

One of the more recent development of an automated drilling system is an assembly for directional drilling on coiled tubing. This system combines several features of the SDD and the automated directional drilling bottomhole assembly, such as the

AUTOTRAK™ brand system, for coiled tubing applications. This coiled tubing system allows drilling of a well path in three dimensions with the capability of a downhole adjustable BUR. The steering ribs are integrated into the bearing assembly of the drilling motor. Other steering features have been adopted from the automated directional drilling bottomhole assembly, such as AUTOTRAK™ brand, with the exception that the steering control loop is closed via the surface rather than downhole. The fast bi-directional communication via the cable inside the coil provides new opportunities for the execution of well path corrections. With the high computing power available at the surface, formation evaluation measurements can be faster processed and converted into a geosteering information and imported into the software for the optimization of directional drilling.

A coiled tubing automated drilling system is disclosed in the United States Serial No. 09/015,848, assigned to the assignee of this application, the disclosure of which is incorporated herein by reference.

The steering-while-rotating drilling systems can be further enhanced through a closed loop geosteering by using the formation evaluation measurements to directly correct the deviations of the course from the planned path. A true navigation can become possible with the integration of gyro systems that withstand drilling conditions and provide the required accuracy. With further automation, the manual intervention can be reduced or totally eliminated, leaving the need to only supervise the drilling process.

Both supervision and any necessary intervention can then be done from remote locations via telephone lines or satellite communication.

The trend in the oil and gas industry is to drill extended reach wells having complex well profiles. Such boreholes may have an upper vertical section extending from the surface to a predetermined depth and one or more portions thereafter which may include combinations of curved and straight sections. For efficient and proper hole forming, it is important to utilize a drill string that has full 3-D steering capability for curved sections and is also able to drill straight sections fast which are not rough or spiraled.

The present invention addresses the above-noted problems and provides a drilling system that is more effective than the currently available or known systems for drilling a variety of directional wellbores.

SUMMARY OF THE INVENTION

The present invention provides a drilling system for drilling deviated wellbores. The drilling assembly of the system contains a drill bit at the lower end of the drilling assembly. A motor provides the rotary power to the drill bit. A bearing assembly disposed between the motor and the drill bit provides lateral and axial support to the drill shaft connected to the drill bit. A steering device provides directional control during the

drilling of the wellbores. A method of controlling a trajectory of a wellbore comprises conveying a drilling assembly in the wellbore by a rotatable tubular member. The drilling assembly includes a drill bit at an end thereof that is rotatable by a drilling motor carried by the drilling assembly. The drilling assembly has a first adjustable stabilizer and a second stabilizer spaced apart from the first stabilizer. The position of a first center of the first adjustable stabilizer is adjusted in the wellbore relative to a second center of the second stabilizer in the wellbore for controlling the trajectory of the wellbore. The position of the first center relative to the second center is based at least in part upon a desired wellbore trajectory stored in a controller on the drilling assembly.

In another aspect, a system for controlling a trajectory of a wellbore comprises a drilling assembly deployed in the wellbore by a rotatable tubular member, the drilling assembly includes a drill bit at an end thereof that is rotatable by a drilling motor carried by the drilling assembly. A first adjustable stabilizer is disposed in the drilling assembly. A second stabilizer is spaced apart from the first adjustable stabilizer. A controller in the drilling assembly adjusts the position of a first center of the first adjustable stabilizer in the wellbore relative to a second center of the second stabilizer in the wellbore for controlling the trajectory of the wellbore. The position of the first center relative to the second center is determined at least in part upon a desired wellbore trajectory stored in the controller in the drilling assembly.

Examples of the more important features of the invention thus have been summarized rather broadly in order that the detailed description thereof that follows may be better understood, and in order that the contributions to the art may be appreciated. There are, of course, additional features of the invention that will be described hereinafter and which will form the subject of the claims appended hereto.

BRIEF DESCRIPTION OF THE DRAWINGS

For detailed understanding of the present invention, references should be made to the following detailed description of the preferred embodiment, taken in conjunction with the accompanying drawings, in which like elements have been given like numerals and wherein:

Figures 1A-1B show examples of well profiles that are contemplated to be drilled according to the systems of the present invention;

Figure 2 shows a schematic of a drilling assembly made according to one embodiment of the present invention for drilling the wellbores of the type shown in **Figures 1A-1B**;

Figure 3 is a schematic view of a drilling system utilizing the drilling assembly of **Figure 2** for drilling wellbores of the types shown in **Figures 1A-1B**;

Figure 4 is a schematic view of a drilling assembly made according to one embodiment of the present invention; and

Figures 5A-D are schematic illustrations of a drilling assembly according to one embodiment of the present invention.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

The present invention provides a self-controlled drilling system and methods for efficiently and effectively drilling vertical, three dimensional curved and inclined straight sections of a wellbore. The operation of the drilling system may be, to any degree, preprogrammed for drilling one or more sections of the wellbore and/or controlled from the well surface or any other remote location.

Figures 1A-1B show examples of certain wellbores which can be efficiently and effectively drilled by the drilling systems of the present invention. The drilling system is described in reference to **Figures 2-3**.

Figure 1A shows a wellbore profile **10** that includes a vertical section **14** extending from the surface **12** to a depth **d1**. The wellbore **10** then has a first curved section **16** having a radius **R1** and extends to the depth **d2**. The curved section **16** is followed by an intermediate section **18** which is a straight section that extends to the depth **d3**. The wellbore **10** then has a second curved section with a radius **R2** that may be different (greater or lesser) from the first radius **R1**. The wellbore **10** is then shown to have a horizontal section **20** that extends to a depth **d4** or beyond. The term "depth" as used herein means the reach of the well from the surface, and may not be the true vertical

depth from the surface. The terms "3D" and "2D" refer to the three-dimensional or two-dimensional nature of the drilling geometry.

Figure 1B shows a well profile **30**, wherein the well has a vertical section **32** followed by a curved section **34** of radius **R1'**, an inclined section **36** and then a second curved section **38** that is curved downward (dropping curved) with a radius **R2'**. The well then has a curved build-up section **40** with a radius **R3'** and section **42** with a radius **R4'**.

The number of the wellbores having well profiles of the type shown in **Figures 1A-1B** is expected to continue to increase. **Figure 2** shows a schematic diagram of a drilling assembly **100** according to one embodiment of the present invention for drilling the above-described wellbores. The drilling assembly **100** carries a drill bit **150** at its bottom or the downhole end for drilling the wellbore and is attached to a drill pipe **152** at its uphole or top end. A drilling fluid **155** is supplied under pressure from the surface through the drill pipe **152**. A mud motor or drilling motor **140** above or uphole of the drill bit **150** includes a bearing section **142** and a power section **144**. The drilling motor **140** is preferably a positive displacement motor, which is well known in the art. A turbine may also be used. The power section includes a rotor **146** disposed in a stator **148** forming progressive cavities **147** there between. Fluid **155** supplied under pressure to the motor **140** passes through the cavities **147** driving or rotating the rotor **146**, the rotor **146** in turn is connected to the drill bit **150** via a drill shaft **145** in the bearing section **142** that rotates the drill bit **150**. A positive displacement drilling motor is described in the Patent

Application Serial Number 09/015,848, assigned to the assignee of the application, the disclosure of which is incorporated herein by reference in its entirety. The bearing section **142** includes bearings which provide axial and radial stability to the drill shaft.

The bearing section or assembly **142** above the drill bit **150** carries a first steering device **130** which contains a number of expandable ribs **132** that are independently controlled to exert desired force on the wellbore inside and thus the drill bit **150** during drilling of the borehole. Each rib **132** can be adjusted to any position between a collapsed position, as shown in **Figure 2**, and a fully extended position, extending outward or radially from the longitudinal axis **101** of the drilling assembly **100** to apply the desired force vector to the wellbore. A second steering device **160** is preferably disposed a suitable distance uphole of the first steering device **130**. The spacing of the two rib devices will depend upon the particular design of the drilling assembly **100**. The steering device **160** also includes a plurality of independently controlled ribs **162**. The force applied to the ribs **162** may be different from that applied to the ribs **132**. In one embodiment, the steering device **160** is disposed above the mud motor **140**. A fixed stabilizer **170** is disposed uphole of the second steering device **160**. In one embodiment, the stabilizer **170** is disposed near the upper end of the drilling assembly **100**. In the drilling assembly configuration **100**, the drill bit **150** may be rotated by the drilling motor **140** and/or by rotating the drill pipe **152**. Thus, the drill pipe rotation may be superimposed on the drilling motor rotation for rotating the drill bit **150**. The steering devices **130** and **160** each have at least three ribs for adequate control of the steering direction at each such device location. The ribs may be extended by any suitable method,

such as a hydraulic system driven by the drilling motor that utilizes the drilling fluid **155** or by a hydraulic system that utilizes sealed fluid in the drilling assembly **100** or by an electro-hydraulic system wherein a motor drives the hydraulic system or an electro-mechanical system wherein a motor drives the ribs. Any suitable mechanism for operating the ribs may be utilized for the purpose of this invention. One or more sensors **131** may be provided to measure the displacement of and/or the force applied by each rib **132** while sensors **161** measure the displacement of and/or the force applied by the ribs **162**. United States Patent Application Serial No. 09/015,848 describes certain mechanisms for operating the ribs and determining the force applied by such ribs, which is incorporated herein by reference. United States Patent No. 5,168,941 also discloses a method of operating expandable ribs, the disclosure of which is incorporated herein by reference.

A set of, preferably three, orthogonally mounted inclinometers **234** determines the inclination of the drilling assembly **100**. The drilling assembly **100** preferably includes navigation devices **222**, such as gyro devices, magnetometer, inclinometers or either suitable combinations, to provide information about parameters that may be utilized downhole or at the surface to control the drilling direction. Sensors **222** and **234** may be placed at any desired location in the drilling assembly **100**. This allows for true navigation of the drilling assembly **100** while drilling. A number of additional sensors **232a-232b** may be disposed in a motor assembly housing **141** or at any other suitable place in the assembly **100**. The sensors **232a-232b** may include a resistivity sensor, a gamma ray detector, and sensors for determining borehole parameters such as

temperature and pressure, and drilling motor parameters such as the fluid flow rate through the drilling motor **140**, pressure drop across the drilling motor **140**, torque on the drilling motor **140** and the rotational speed (r.p.m.) of the motor **140**.

The drilling assembly **100** may also include any number of additional sensors **224** known as the measurement-while-drilling devices or logging-while-drilling devices for determining various borehole and formation parameters or formation evaluation parameters, such as resistivity, porosity of the formations, density of the formation, and bed boundary information.

A controller **230** that includes one or more microprocessors or micro-controllers, memory devices and required electronic circuitry is provided in the drilling assembly. The controller receives the signals from the various downhole sensors, determines the values of the desired parameters based on the algorithms and models provided to the controller and in response thereto controls the various downhole devices, including the force vectors generated by the steering devices **130** and **160**. The wellbore profile may be stored in the memory of the controller **230**. The controller may be programmed to cause the drilling assembly to adjust the steering devices to drill the wellbore along the desired profile. Commands from the surface or a remote location may be provided to the controller **230** via a two-way telemetry **240**. Data and signals from the controller **230** are transmitted to the surface via the telemetry **240**.

Figure 3 shows an embodiment of a land-based drilling system utilizing the drilling assembly **100** made according to the present invention to drill wellbores according to the present invention. These concepts and the methods are equally applicable to offshore drilling systems or systems utilizing different types of rigs. The system **300** shown in **Figure 3** has a drilling assembly **100** described above **(Figure 1)** conveyed in a borehole **326**. The drilling system **300** includes a derrick **311** erected on a floor **312** that supports a rotary table **314** which is rotated by a prime mover such as an electric motor **315** at a desired rotational speed. The drill string **320** includes the drill pipe **152** extending downward from the rotary table **314** into the borehole **326**. The drill bit **150**, attached to the drill string end, disintegrates the geological formations when it is rotated to drill the borehole **326**. The drill string **320** is coupled to a drawworks **330** via a kelly joint **321**, swivel **328** and line **329** through a pulley (not shown). During the drilling operation the drawworks **330** is operated to control the weight on bit, which is an important parameter that affects the rate of penetration. The operation of the drawworks **330** is well known in the art and is thus not described in detail herein.

During drilling operations, a suitable drilling fluid **155** from a mud pit (source) **332** is circulated under pressure through the drill string **320** by a mud pump **334**. The drilling fluid **155** passes from the mud pump **334** into the drill string **320** via a desurger **336**, fluid line **338** and the kelly joint **321**. The drilling fluid **155** is discharged at the borehole bottom **351** through an opening in the drill bit **150**. The drilling fluid **155** circulates uphole through the annular space **327** between the drill string **320** and the borehole **326** and returns to the mud pit **332** via a return line **335**. A sensor S_1 preferably placed in the line **338** provides information about the fluid flow rate. A surface torque sensor S_2 and a sensor S_3 associated with the drill string **320** respectively provide information about the torque and the rotational speed of the drill string. Additionally, a sensor S_4 associated with line **329** is used to provide the hook load of the drill string **320**.

In the present system, the drill bit **150** may be rotated by only rotating the mud motor **140** or the rotation of the drill pipe **152** may be superimposed on the mud motor rotation. Mud motor usually provides greater rpm than the drill pipe rotation. The rate of penetration (**ROP**) of the drill bit **150** into the borehole **326** for a given formation and a drilling assembly largely depends upon the weight on bit and the drill bit rpm.

A surface controller **340** receives signals from the downhole sensors and devices via a sensor **343** placed in the fluid line **338** and signals from sensors $\mathbf{S_1}$, $\mathbf{S_2}$, $\mathbf{S_3}$, hook load sensor S_4 and any other sensors used in the system and processes such signals according to programmed instructions provided to the surface controller **340**. The surface controller **340** displays desired drilling parameters and other information on a display/monitor **342**

and is utilized by an operator to control the drilling operations. The surface controller **340** contains a computer, memory for storing data, recorder for recording data and other peripherals. The surface controller **340** processes data according to programmed instructions and responds to user commands entered through a suitable device, such as a keyboard or a touch screen. The controller **340** is preferably adapted to activate alarms **344** when certain unsafe or undesirable operating conditions occur.

The method of drilling wellbores with the system of the invention will now be described while referring to **Figures 1A-3**. For the purpose of this description, the drilling of the vertical hole sections, such as section **14** and other straight sections, such as sections **18** and **20** of **Figure 1A** is also referred to as two-dimensional or "2D" holes. The drilling of the curved sections, such as section **16** of **Figure 1A** and sections **34, 38,** and **42** is referred to as three dimensional or "3D" drilling.

Referring to **Figure 1A**, to form a vertical section, such as section **14 (Figure 1A)**, the ribs **132** of the steering device **130** are adjusted to exert the same side force by each rib **132**. However, the rib forces are preferably individually controlled to better maintain verticality. The ribs **162** of the second steering device **160** may also be adjusted in the same manner. The drilling is then performed by rotating the drill bit **150** by the drilling motor **140**. If desired, the drill pipe **152** may also be rotated from the surface at any speed if the same force is applied to all the ribs or alternatively at relatively low speed if the ribs are individually controlled. The controller **230** determines from the inclination sensor measurements if the drill string **387** has deviated from the true vertical.

The controller, in response to the extent of such deviation, adjusts the force vectors of one or more ribs of the steering devices **130** and/or **160** to cause the drill bit **150** to drill along the true vertical direction. This process continues until the drill bit **150** reaches the depth **d1**.

To initiate the drilling of the curved section **16**, the drilling direction is changed to follow the curve with the radius **R1**. In one mode, a command signal is sent by the surface controller **340** to the downhole controller **230**, which adjusts the force vectors of the ribs of one or both the steering devices **130** and **160** to cause the drill bit **150** to start drilling in the direction of the planned curve (path). The controller **230** continues to monitor the drilling direction from the inclination and navigation sensors in the drilling assembly **100** and in response thereto adjusts or manipulates the forces on the ribs **132** and/or **162** in a manner that causes the drill bit to drill along the curved section **16**. The drilling of the 3-D section **16** is performed by the drilling motor **140**. The drill string **387** is not rotated from the surface. In this mode, the drilling path **16** and algorithms respecting the adjustments of the rib force vectors are stored in the controller **230**. In an alternative mode, the drilling direction and orientation measurements are telemetered to the surface and the surface controller **340** transmits the force vectors for the ribs, which are then set downhole. Thus, to drill a 3D section, the drilling is performed by the motor, while the rib force vectors are manipulated to cause the drill bit to drill along the curved section. The above described methods provide a self-controlled closed loop system for drilling both the 2D and 3D sections.

To drill an inclined section, such as section **18**, the drilling may be accomplished in two different ways. In one method, the drill string is not rotated. The drilling is accomplished by manipulating the force on the ribs. Preferably both rib steering devices **130** and **160** are utilized. To drill the straight section **18**, the force for the various ribs, depending upon the rib location in the wellbore, are calculated to account for the inclination and the gravity effect. The forces on the ribs are set to such predetermined values to drill the inclined section **18**. Adjustments to the rib forces are made if the drilling deviates from the direction defined by the section **18**. This may be done by transmitting command signals from the surface or according to the programs stored in the controller **230**.

Alternatively, the drill bit rotation of the drilling motor is superimposed with the drill string rotation. The ribs of the steering device are kept at the same force. One or both steering devices **130** and **160** may be used. During the rotation of the drill string, the directional characteristics can be adjusted by the same adjustment of the radial displacement of the ribs or through the variation of the average force to the ribs, which is equivalent to a change of the stabilizer diameter. The use of both sets of the ribs enhances this capability and also allows a higher build-up rate. Rotating the drill string lowers the friction and provides better hole cleaning compared to the mode wherein the drill string is not rotated.

The force vectors for drilling a straight section in one mode of operation are computed at the surface. When the drill bit reaches the starting depth for such a section,

the surface controller **340** sends command signals to the downhole controller **230**, which sets all the ribs of the desired steering device to a predetermined force value. The drilling system then maintains the force vectors at the predetermined value. If the inclination of the drilling assembly differs from that of the desired inclination, the downhole controller adjusts the force vectors to cause the drilling to occur along the desired direction. Alternatively, command signals may be sent from the surface to adjust the force vectors. Horizontal sections, such as section **20**, are drilled in the same manner as the straight inclined sections. The curved sections, such as section **38**, are drilled in the 3D manner described earlier.

In another embodiment, shown in **Figures 4A-C**, bottomhole assembly (BHA) **420** is attached to a tubular string **401** and disposed in deviated wellbore **405**. As shown, wellbore **405** is substantially horizontal, but may be any inclination, or deviation, from vertical. Wellbore **405** may also be three dimensional such that it extends at some angle from the plane of the paper as represented in **Figs. 4A-C**. Wellbore **405** has centerline **409**. Drill bit **408** is attached to the bottom of BHA **420** and acts to disintegrate formation **421** as it is rotated in contact with formation **421** by drilling motor **415**. Drilling motor **415** may be a positive displacement motor or, alternatively a mud turbine, both of which are known in the art. The outer diameter **422** of drill bit **408** is called the gage diameter that essentially establishes the diameter of wellbore **405**. The base diameter of the tubular members attached above drill bit **405** are typically smaller in diameter than the gage diameter. Lower stabilizer **406** is part of bottomhole assembly **420** and is located a predetermined distance from bit **408**. Lower stabilizer **406** has multiple ribs **407** that may

be independently adjusted to extend out and contact the wall of wellbore **405** and exert a force on wall of wellbore **405**. The ribs may be actuated by a hydraulic system, an electro-hydraulic system wherein a motor drives the hydraulic system and/or an electro-mechanical system wherein a motor drives the ribs using mechanical power transmission elements such as gears (not shown). Any suitable mechanism for operating the ribs may be utilized for the purpose of this invention. Lower stabilizer **406** also acts as a bearing housing for the drive shaft of drilling motor **415** such that the adjustable ribs only rotate when tubular string **401** rotates.

Upper stabilizer **402** is disposed in the BHA **420** a predetermined distance uphole from adjustable stabilizer **406**. In one embodiment, upper stabilizer **402** is a fixed blade stabilizer having a plurality of blades. The blades may be straight or, alternatively, may be spiral in shape. The outer diameter of the blades **403** on upper stabilizer **402** is on the order of ¼ to ½ inch smaller than the gage diameter of drill bit **405**. Alternatively, upper stabilizer **402** may be an adjustable stabilizer having a plurality of blades extendable a predetermined distance such that the outer diameter of the extended blades is undergage. The force of gravity F_g acts to create a pendulum effect in BHA **420**. The lack of wall contact on the top of upper stabilizer blades **403** provides a more limber assembly that may be more easily deflected than the BHA would be with an in-gage stabilizer at the same location as the undergage upper stabilizer **402**. As shown in **Fig. 4A**, the gravitational force acts to force BHA **420** against the bottom side of wellbore **405**, forcing contact on blades **403** and **407** of upper stabilizer **402** and lower stabilizer **406**, respectively. At wall contact, the undergage diameter of stabilizer **402** places the center **404** of stabilizer **402** below the centerline **409** of wellbore **405**. By adjusting the

extension of ribs **407**, the center **410** of lower stabilizer **406** may be positioned above, below, or coincident with center **404** as indicated by arrows **426**. This variable positioning of the center **410** with respect to the center **404** allows the BHA **420** to bend and be directed along a predetermined path in a pendulum action known in the art. BHA **420** has a processor and sensors as described previously with respect to **Fig. 2**. The processor has a predetermined trajectory stored therein and uses sensors to determine the position of the BHA **420** with respect to the predetermined trajectory. The processor calculates deviations from the predetermined trajectory and adjusts the position of the center **410** to maintain the current trajectory **411** or to move the center to positions **410'** and **410''**, for example, to create building or dropping trajectories as shown by paths **411'** and **411''** in **Figs. 4B** and **4C**, respectively.

As one skilled in the art will appreciate, various combinations of lower and upper adjustable stabilizer configurations are possible for steering the bottomhole assembly along the desired trajectory. Exemplary configurations are shown in **Figure 5A-D**, where a **M** indicates a drilling motor, **A** indicates a stabilizer that is adjusted to control the wellbore path and **F** indicates a stabilizer whose blades are held in a fixed position during a particular directional section. Note that the **F** stabilizer may have mechanically fixed blades, such as welded on blades, or may have adjustable blades that are held at a predetermined position during the drilling of a particular section. Thus, both stabilizers may be adjustable stabilizers with one held at a predetermined extension to simulate a fixed stabilizer.

While the previous discussion was primarily directed to pendulum action due to gravity in substantially the vertical plane, one skilled in the art will appreciate that the

system described is also capable of steering in the horizontal, or azimuth plane. In operation, without string rotation, multiple combinations of stabilizer extensions may be used to control the trajectory. The extension of one or more adjustable ribs enables the path to be steered in a 2 or 3 dimensional trajectory. For example, one stabilizer (upper or lower) may be pushed to the side by the extension of one or more ribs while the other stabilizer is has all of its ribs equally extended at a predetermined position. The predetermined position may be full gage or under gage. In another example, both stabilizers may have there ribs extended to simulate two predetermined diameters that in effect result in a full gage/underage combination to enable the pendulum control described previously. This under gage/full gage configuration is also usable with string rotation. In yet another example, both stabilizers may be pushed to the side by having at least one rib of each stabilizer radially extended.

Thus, the present invention provides an adjustable pendulum drilling system which can be used to drill a curved hole and then a straight inclined and/or horizontal section. The curved section can be a build-up angle section or drop angle section. The system includes a full directional sensor package and a control unit along with control models or algorithms. These algorithms include downhole adjustable build-up rates needed and the automated generation and maintenance of the force vectors and/or rib displacements. This eliminates the need for tedious manual weight-on-bit and tool face control commonly used. The true navigation becomes possible with the integration of gyro systems. This automated system substantially reduces the manual intervention, leaving the need to only supervise the drilling process.

The system of the present invention which utilizes the motor with the ribs that automatically adjusts side forces, pendulum effects and the steering direction closes the gap that exists between the conventional steerable motors with a fixed bend and the steering-while-rotating systems. Because the system of the present invention allows fine tuning the directional capability while drilling, and because of no need for time consuming tool face orientations, such systems often have significant benefits over the steerable motor systems. The systems of the present invention result in faster drilling and can reach targets in greater lateral reach.

The foregoing description is directed to particular embodiments of the present invention for the purpose of illustration and explanation. It will be apparent, however, to one skilled in the art that many modifications and changes to the embodiment set forth above are possible. It is intended that the following claims be interpreted to embrace all such modifications and changes.